

MODELING BLAST WAVE PROPAGATION IN A GENERIC FACILITY

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ABSTRACT

The blast environment inside a building resulting from an internal detonation is a coupled fluid and structural dynamics problem that depends on the extent of failure of the interior walls surrounding the blast. As the walls fail, the propagating airblast convects the wall debris to adjacent rooms, creating an hazardous environment. To improve our understanding of internal blast damage and fragment dispersion phenomena associated with transient and quasi-static loadings, the Defense Threat Reduction Agency (DTRA) has initiated a combined experimental and computational effort. The program investigated the response of interior walls made of various materials to blast loading. This paper will describes the numerical methodology, the application of the coupled computational fluid dynamics (CFD) and computational structural dynamics (CSD) methodology to the study of concrete masonry unit (CMU) walls response to a blast in the detonation (main) room, and prediction comparisons to experimental data.

INTRODUCTION

Over the past years we have seen a proliferations of fast-running codes, intended to predict the effect of external detonations, expressed as airblast loading on structures, and the structural response to such loading. These fast-running codes can be based on either empirical equations or look-up tables, and most-recently, even coarse-grain first-principles codes. In comparison, very little effort has been expended on developing such as fast running predictive methodology for internal detonations, no doubt due to the significantly more complex environment resulting from multiple reflections from adjacent walls, blast propagation through wall openings, debris loadings, etc. To remedy this deficiency, the Defense Threat Reduction Agency (DTRA) has embarked on a program to investigate the blast environment and the response of building interior walls subjected to loading from internal detonations. The program indents to generate experimental data for validation of first-principles as well as future fast-running codes used in weapon effects planning tools, initiate the development of fast running engineering models and help calibrate first-principles based coupled computational fluid dynamics (CFD) and computational structural dynamics (CSD) models¹⁻⁴ for prediction of wall response to blast and

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debris. This paper describes the numerical results as well as some experimental data obtained in a single test of this large and evolving program.

Technical Approach

Mesh generation for both CSD and CFD is performed using FRGEN3D⁵. This unstructured grid generator is based on the advancing front method. The CFD mesh is composed of triangular (surface) and tetrahedral (volume) elements. The CSM mesh includes beams, triangular or quad shells and bricks for the solids.

The flow solver employed is FEFLO, a 3-D adaptive, unstructured, edge-based hydro-solver based on the Finite-Element Method Flux-Corrected Transport (FEM-FCT) concept⁶. It solves the Arbitrary Lagrangean-Eulerian (ALE) formulation of the Euler and Reynolds-averaged turbulent, Navier-Stokes equations. The code includes a large variety of state-of-the art numerical shock-capturing schemes, from FCT, exact or approximate Riemann, to ENO to HLLC, and from second-order to eight-order accuracy, a choice that is continuously updated as new schemes are developed. The spatial mesh adaptation is based on local H-refinement, where the refinement/deletion criterion is a modified H2-seminorm⁶ based on a user-specified criteria. FEFLO supports various equations of states including real air, water, SESAME and JWL with afterburning, and has been coupled to CHEETAH⁹. Particles are treated as a solid phase, exchanging mass, momentum and energy with the fluid.

The structural dynamics solvers used was SAICSD^{7,8}. This code solves the continuous mechanics equilibrium equation. The weak formulation (virtual work principle) is written in the spatial configuration (actual configuration) and it is discretized in time using an explicit second-order central difference scheme. In space, the virtual work equation is solved by using stable finite element types. The most used elements are: a full integrated large-deformation Q1/P0 solid element (hexahedra with an 8 nodes interpolation scheme for the cinematic variables and constant pressure) which does not present hourglass modes and it does not lock for incompressible cases. Several 3-node and 4-node large-deformation shell elements (Hughes-Liu shell, Belytschko shells, MITC shells, ASGS stabilized shells) which are formulated using standard objective stress update schemes (Jaumann-Zaremba, co-rotational embedded axis, etc.), are fully integrated to avoid hourglass spurious modes. Finally, some objective truss and beam elements (i.e. Belytschko and Hughes-Liu beams) have also been implemented. Many different material models have been included into the code. The most used are: a plasticity model which relies on a hyper-elastic characterization of the elastic material response for the solid elements, and a standard hypo-elastic plasticity model for the shell, beam and truss elements. The most often used failure criterion is based on the maximum effective plastic strain and the stress tensor inside the element. The fracture may be simulated by element erosion and/or node disconnection.

RESULTS

For this test, all four rooms of the facility were modeled. To help clarify the terminology, we refer to bay 1 as the room closest to the detonation room (Fig 1), while bay 3 is the furthest from the detonation room. The test walls are labeled test walls 1 through 4, where test wall 1 is the wall between the detonation room and bay 1. Other tests used walls materials representative of interior partition walls, such as steel or wood stud walls with gypsum wall board sheating. Here the test included 6" normal-weight concrete masonry units (CMU). The CMU conformed to ASTM C-90 specifications for grade "N" units with $f'_m = 1500$ psi. The explosive source consisted of a bare explosive located in the detonation room at a height of approximately three feet above the floor.

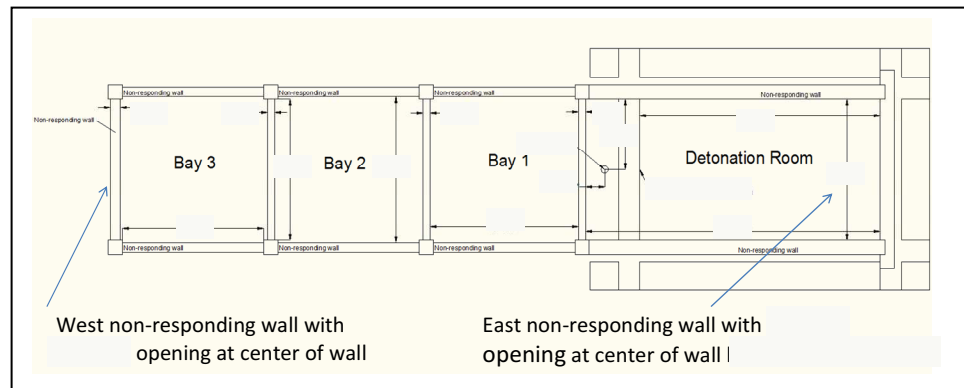


Fig 1. Schematics of the facility

Sixteen pressure gages were fielded, eight of which, placed on the ceiling, are marked in Fig 2. Two blast pressure gages were placed on the ceilings of the detonation room, Bay 1 and Bay 2. Bay 3 only had 2 blast pressure gages. A pressure gage was also installed in the center of the test walls in Bays 1 and 2.

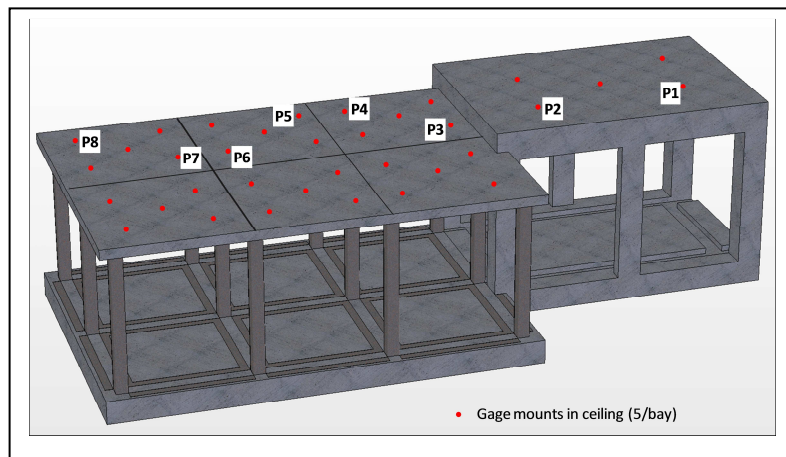


Fig 2. Station gage locator.

The numerical integration was initiated with a bare charge detonated some distance from the wall. The computational approach used a staggered mesh. Rather than using the more expensive adaptive refinement procedure, where the mesh is adapted to the flow gradients every 7 time steps, we used an approach we have developed and applied successfully on notebook computers¹⁰. We start with a small domain which includes the explosive, and interpolate the solution to successively-larger domains as the simulation progresses. Each domain contained about 120 million elements, concentrated at the zone of interest.

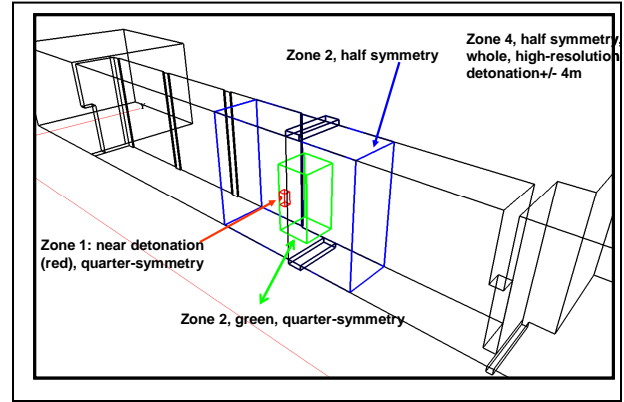


Fig 3. Coarse-grain adaptive meshing strategy.

Interpolation from one domain to the next is automatic, triggered by the shock wave arrival to pre-defined "sensing stations". A schematics for this procedure is shown in Fig. 3.

Figures 4 shows pressure and velocity contours at $3\mu\text{s}$, $63\mu\text{s}$, $93\mu\text{s}$, $203\mu\text{s}$, 0.2ms , and 0.3ms , respectively. The approach outlined above enables an extremely accurate modeling of the detonation event. This explosive was modeling using the FEFLO code coupled with Cheetah⁹, as energy is being released long after detonation has been completed. The results shows the seamless integration from zones 1 through 3, as the blast wave expands.

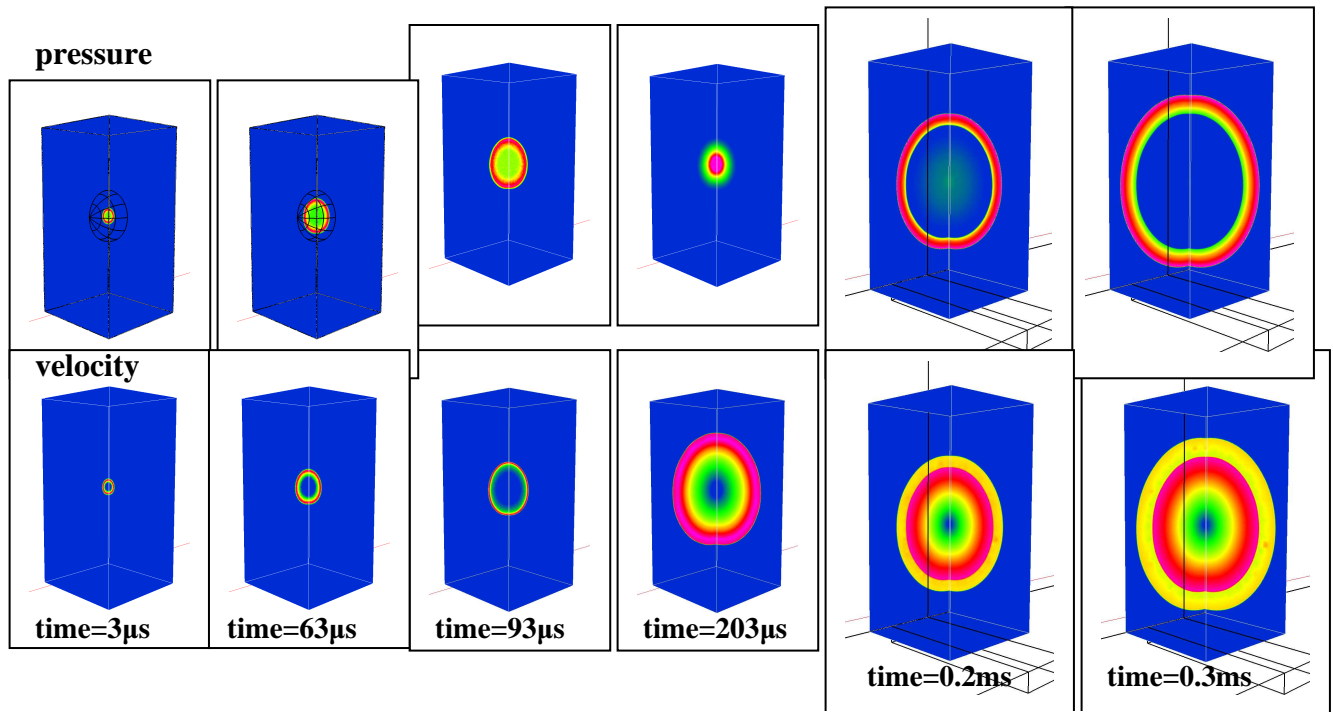


Fig 4. Pressure and velocity contours at times of $3\mu\text{s}$, $63\mu\text{s}$, $93\mu\text{s}$, $203\mu\text{s}$, 0.2ms , and 0.3ms , respectively.

Figures 5a through 5c show superimposed pressure contours on the plane-of-symmetry and the rigid surfaces, and CSD velocity contours on the CMU walls at times of 1.0ms, 10.0ms and 25.0ms, respectively. The blast wave impacts the wall at about 0.85ms. At 1.0ms (Fig 5a) we observe the initiation of wall breach nearest the charge, at the nearest stagnation point. For an HOB near a wall we typically expect to observe two high-pressure locals: 1. the point on the wall nearest the charge (i.e., same height as the HOB), where the flow stagnates; and 2. at the nearest corner (actually, plane-of-symmetry at ground level), the second stagnation point. These high-pressure locations are observed in Figs 5a and 5b, resulting in high-velocity of the responding CMU blocks, as shown at later times in Figs 5b and 5c, at 10ms and 25ms, respectively.

The pressure contours at later times show blast wave reverberation within the detonation room, with continuous release through the opened 'door'. As the breach occurred at later times we observe a strong jetting into bay 1, due to the gradual opening of the breach. Hence, we would not expect to see strong shocks in Bay 1, and certainly, not in further-out bays.

The response of the complete wall 1 is depicted in Figs 6. The results show the wall breach at the HOB blast level and at the stagnation point on the bottom of the plane-of-symmetry. The results at later times show that the wall response is controlled by the exerted pressure: increased CMU velocity at all points where stagnation and hence, higher blast pressures, are expected. These include the two initial breach points, as well as the other stagnation points: the top of the plane-of-symmetry, and wall corners (top and bottom). The CMU velocity at all points on the wall directly correlates with the pressure observed.

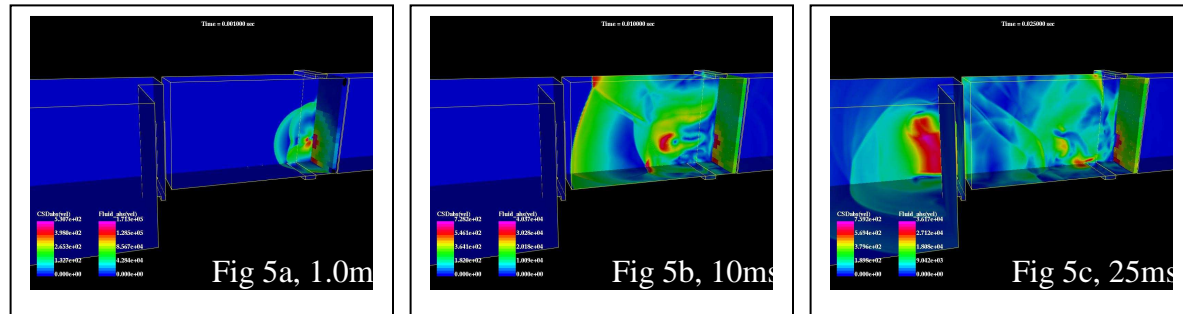


Fig 5. Composite snapshots of pressure contours on the plane-of-symmetry and other rigid surfaces, and CSD velocity on Wall1 (CMU) at 1.0ms, 10.0ms and 25ms, respectively.

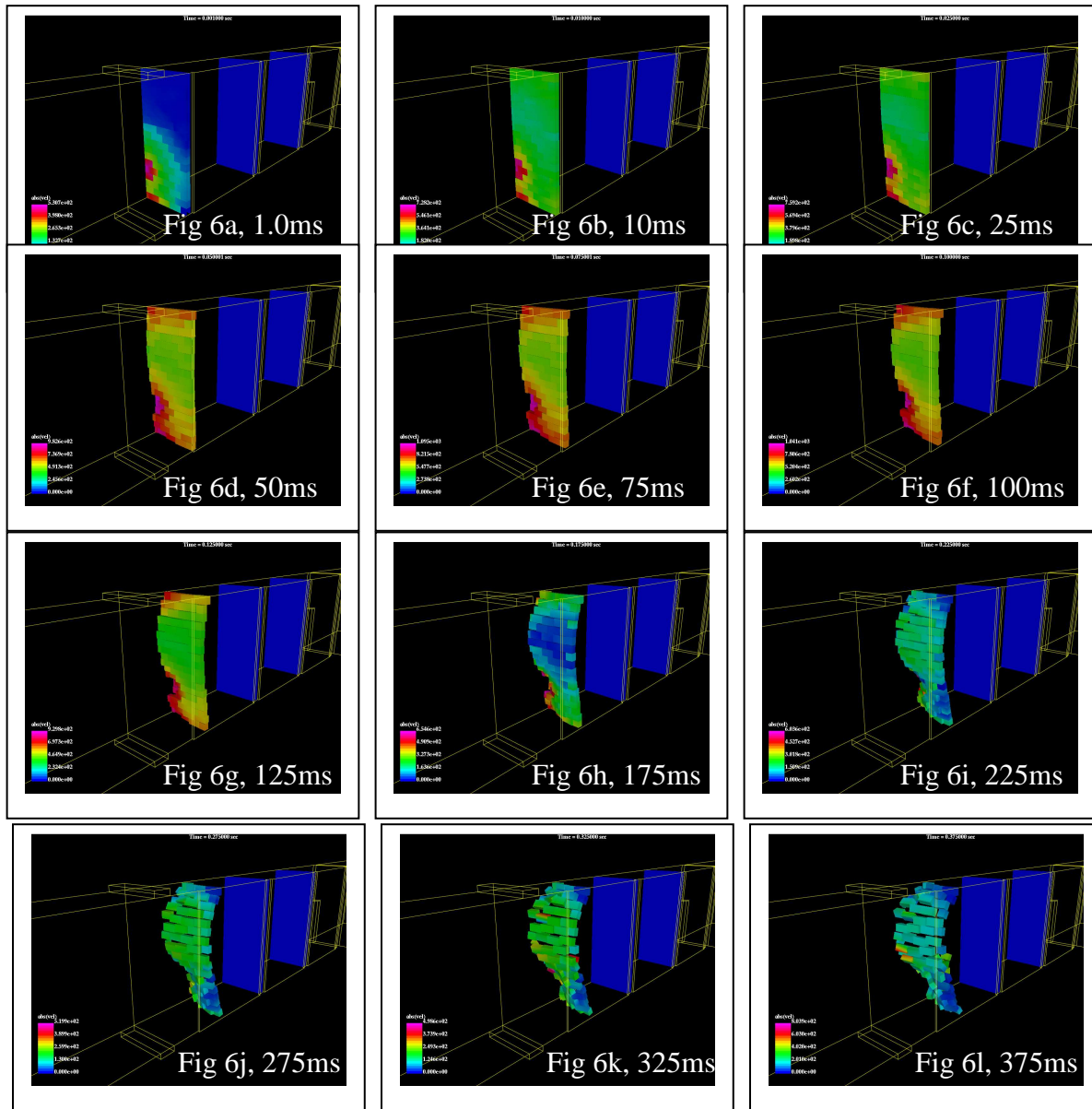


Fig 6. CSD velocity contours describing the response of Wall 1 at several times showing wall breach and complete wall movement. CMU velocity is controlled by the exerted pressure.

Comparison of pressure time histories between measured and predicted results at several locations is shown in Fig 7. Stations P1 and P2 are located on the ceiling of the blast room (Fig 2), where P2 is closer to the charge than P1. The predicted pressure contours show results of three simulations: the first modeled CMU walls with no mortar and rigid individual CMU units, the second modeled rigid (non-responding) walls, while the third modeled CMU walls where mortar has been added between the CMU blocks, but the blocks were not allowed to deform. The results show that while the initial shock time-of-arrival, peak value and impulse were predicted very accurately, the simulation at later time under-predicts the measured impulse. This can result from either under-predicting the amount of energy released, or over-predicting the energy required to break the mortar. As this coupled code⁹ (FEFLO and CHEATAH) has been used previously very successfully to model the afterburn of this explosive, this issue remains unsolved. It should be noted that after conducting the simulation, we visited the facility and discovered that the as-built facility 'doors' are a larger than modeled (as the modeling was based on the design data). Still, it remains to be proven that this change will be sufficient to explain the energy deficiency.

Comparison of results for the stations located in Bay 1, stations P3 and P4, show that the simulations correctly predicted the wall breach and the initial jetting timing and peak values. The computational solution discontinuity occurs due to the CMU unit passing very close in to the CFD cell where the numerical pressure transducer is located, a numerical artifact resulting from the embedded approach to coupling of CFD and CSD, but also fairly similar to what a experimental pressure transducer would observe. Note that the simulation with mortar indicate lower wall velocities, as well as later arrival of peak values

Future simulations will model the facility as built, while adding structural response of the CMU unit, as the results of the test indicate that most CMU blocks were broken, and energy required to break these must be included in the model.

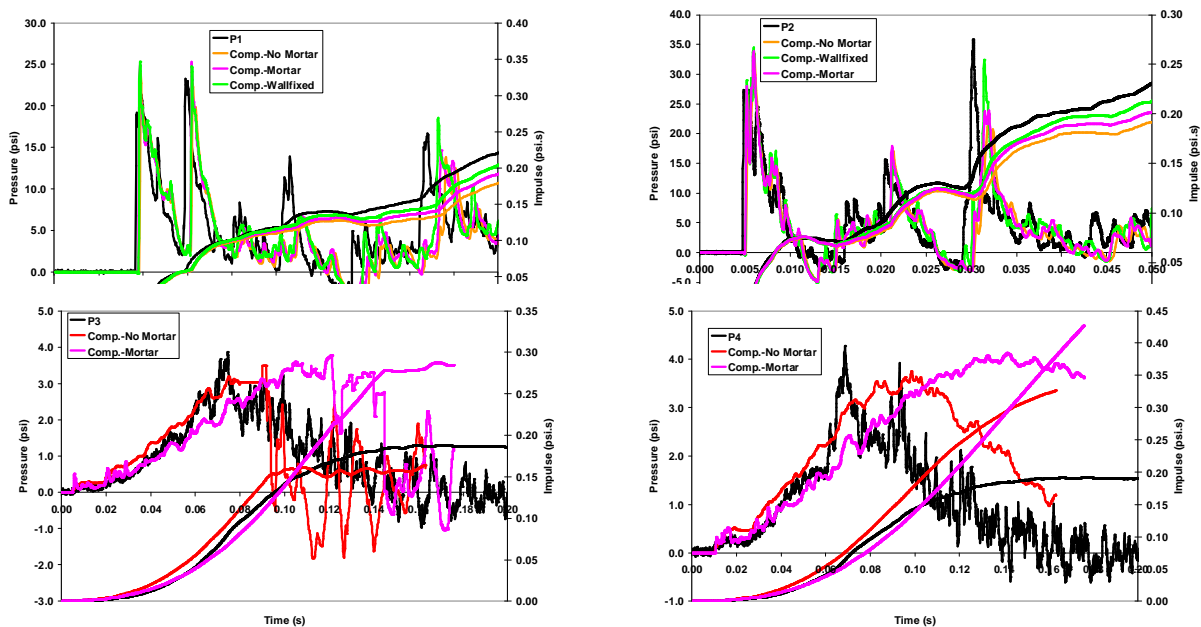


Fig 7. Comparison of measured and predicted pressure and impulse values at the detonation room (P1 and P2) and Bay 1 (P3 and P4).

CONCLUSIONS AND SUMMARY

The Defense Threat Reduction Agency (DTRA) has initiated a combined experimental and computational effort intended to improve our understanding of internal blast damage and fragment dispersion phenomena. The program encompassed both experiments and numerical simulations that investigated the response of interior walls made of various materials to blast loading.

The test case modeled in this paper included non-reinforced CMU walls between the detonation room and the adjacent bay, as well as between all other bays. The approach taken was to model the non-ideal explosive detonation using a coupling of FEFLO and CHEETAH, and the structural response to the blast loading using the coupled CFD and CSD methodology, where the structural domain is embedded within the fluid domain.

Several computations were conducted., modeling the CMU blocks as rigid, with and without mortar. Comparison of the predictions to the test results show good agreement in the detonation room. Both predictions and videos taken during the test show that the response of the masonry walls was primarily a function of blast pressure and impulse, and impact loading of wall debris (for walls 2 and 3). While the pressure growth as well as peak pressure and impulse values in Bay 1 are modeled accurately, it is clear that to accurately predict the quasi-steady pressure in all bays we must account for the structural response of the CMU blocks, rather than model them as rigid. The post-test results showed that all CMU blocks in walls 1 and 2 were broken. In addition, the as-built opening in the blast room was larger than originally planned (and modeled), an issue that will be addressed in future, repeat simulations.

Acknowledgements

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